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2D symmetry and pinning of quantum-Hall "strip phase"

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Abstract. Recent experiments on (001) GaAs/AlGaAs structures revealed a new phase in the excited Landau levels. The results can be related to spontaneous formation of unidirectional charge density waves ("strip phase"). We address to the unsolved problem: why stripes are pinned coherently across the sample along [110]. Developing the Kroemer's idea about the role of C_{2v} symmetry in this system we show that for (001) A_3B_5 single heterojunction the conduction band in-plane effective mass is anisotropic. This anisotropy and the optical anisotropy in heterostructures with different cations and anions have the same origin. Although very weak, the difference in the conduction band effective masses along the crystallographic [110] and [$1\bar{1}0$] axes may define the direction of the stripes. The results agree with the experiments in tilted magnetic fields.

Recent studies of ultra-high quality 2D electron systems in (001) GaAs/AlGaAs heterojunctions near half-integer filling factors $\nu \geq 9/2$ at very low temperatures [1, 2, 3] revealed a new class of correlated many-electron states which is believed to be related to predicted in [4] spontaneous formation of charge density waves ("strip phase"). This hypothesis is based on the observation of a giant magnetoresistance anisotropy in such systems, the longitudinal resistances in the two perpendicular crystallographic [110] and [$1\bar{1}0$] directions have a ratio $R_{xx}/R_{yy} \sim 5{-}3500$ (depending on the way of measurements), [110] being the direction of low resistance. Also it was shown [2, 3] that the in-plane magnetic field $B_{\|}$ as strong as ~ 1 T may reorient the directions of low and high resistances. The conclusion that for high in-plane fields the high resistance axis is parallel to the direction of the in-plane field was made [3]. Similar results for $B_{\|}$ along [110] at all half-integer $\nu \geq 9/2$ and for $B_{\|}$ along [$1\bar{1}0$] at $\nu = 11/2$ and $\nu = 15/2$ were obtained in [2]. The authors of [5] came to the same result through the Hartree–Fock calculations. They found also that at $B_{\|} = 0$ the native anisotropy energy that determines the preferred orientation of the in-plane stripes of alternating charge density is less than only $k_B 10$ mK per electron. However, the origin of the native mechanism making the stripes coherent over the macroscopic size of the studied samples at is still not uncovered. It is one of the basic unsolved problems.

Here we are developing the idea of Kroemer [6] that it is C_{2v} symmetry of the heterostructure potential confining 2D electron gas that may lead to the effect. Briefly, we will show that due to the asymmetric potential of the heterojunction there exists the native anisotropy of the in-plane conduction band effective mass (EM), and it has the same order in magnitude as the anisotropy of EM induced by the in-plane magnetic field of magnitudes used in the above experiments. Also, due to the combined effect of the Dresselhaus and Rashba terms the spin-orbit interaction is anisotropic [7]. This type of the native anisotropy and its effect on the quantum-Hall strip phase is not discussed here. It requires further study.

To consider the problem one starts from the the one-particle EM equation for electrons in a (001) A_3B_5 heterostructure with a single heterojunction. It was shown [8] that the properly

constructed many-band system of envelope-function equations preserves information about the lowered symmetry of the heterostructure (C_{2v}) as compared to the symmetry of the host materials (T_d). The light hole-heavy hole mixing at the center of 2D Brillouin zone is one of the consequences of the symmetry lowering [9]. This mixing leads to the giant optical anisotropy (with the same principal axes [110] and [$1\bar{1}0$]) in heterostructures composed of materials with different cations and anions observed experimentally [10]. It is obvious that the symmetry C_{2v} should manifest itself in EM equation for conduction band too. However, the derived in [8] one-band effective Hamiltonian for electrons lost C_{2v} symmetry information. To construct the effective Hamiltonian having C_{2v} symmetry means that now we should go beyond the approximation used in [8] and consider smaller but important here anisotropic terms. Because of the limiting accuracy of the method [8], we might not allow for them if we were interested merely in more precise calculation of the conduction band states. Such contributions may be taken into account just because they provide the symmetry lowering—the effect which is absent without them. So, as we are not interested here in terms of symmetry higher than C_{2v}, the effective Hamiltonian may include only the leading potential and kinetic energy terms (used in standard EM approximation) and the leading anisotropic term which will be found below.

We may obtain the correct Hamiltonian having C_{2v} symmetry via the method of invariants. Setting the spin-orbit interaction aside (we will not discuss it here) one may conclude, that the information about C_{2v} symmetry should be found in the kinetic energy operator. If we assume that the in-plane components of momentum $\hat{p}_x \parallel [100]$ and $\hat{p}_y \parallel [010]$, then the most general form of the quadratic in the in-plane momentum kinetic energy operator has the following form

$$\hat{T} = \frac{\hat{p}_x^2 + \hat{p}_y^2}{2m^*} + \mathcal{A}\frac{1}{2}(\hat{p}_x\hat{p}_y + \hat{p}_y\hat{p}_x). \tag{1}$$

Here m^* is the conduction band EM, $\mathcal{A}$ defines the in-plane EM anisotropy. From the derived in [8] many-band system of envelope-function equations we have indeed

$$\mathcal{A}(z) = \delta(z){\sum_{n,n'}}' \frac{2\langle s \mid \hat{p}_x \mid n\rangle D_{nn'}\langle n' \mid \hat{p}_y \mid s\rangle + 4D_{sn}\langle n \mid \hat{p}_x \mid n'\rangle\langle n' \mid \hat{p}_y \mid s\rangle}{m_0^2(\epsilon_s - \epsilon_n)(\epsilon_s - \epsilon_{n'})}. \tag{2}$$

Here $\delta(z)$ is the Dirac δ-function, $z = 0$ defines the position of the heterointerface, $\langle n \mid \hat{p}_\alpha \mid n'\rangle$ is α-component of the interband (for bands n and n' at Γ-point) matrix element of momentum, s is the conduction band index, m_0 is the free electron mass, and ϵ_n means the nth band edge energy of a host material. The parameter

$$D_{nn'} = \sum_{j=\pm1,\pm2,\ldots} \frac{\langle n \mid \delta U \sin(4\pi jz/a) \mid n'\rangle}{4\pi j/a} \int_{-\infty}^{\infty} \frac{dG(z)}{dz} \cos\left(\frac{4\pi}{a}jz\right) dz. \tag{3}$$

Here a is the lattice constant. The appearing in the above expression functions are defined the way the crystalline potential of the heterostructure is

$$U(\mathbf{r}) = U_1(\mathbf{r}) + G(z)\delta U(\mathbf{r}), \tag{4}$$

U_1 is the crystalline potential of one of the materials of the heterojunction, and $U_2 = U_1 + \delta U$ is that of another one. Note, that parameter D_{XY} defines the light hole-heavy hole

mixing at the center of 2D Brillouin zone, here X and Y are indexes of the Bloch functions of the valence Γ_{15} band edge (transforming like x and y under symmetry operations of the group T_d) [8, 9].

If we perform the 45°-rotation of the coordinate system, so that in new coordinates $x\|[1\bar{1}0]$ and $y\|[110]$, and then add magnetic field $\mathbf{B}$ with the gauge of the vector potential $\mathbf{A} = (B_y z, -B_x z + B_z x, 0)$, the conduction band Hamiltonian will take the form (without spin-orbit interaction)

$$\begin{aligned} \hat{H} &= \frac{\hat{p}_z^2}{2m^*} + V(z) + \frac{1}{2}\left(\frac{1}{m^*} - \mathcal{A}(z)\right)\left(\hat{p}_x + \frac{e}{c}B_y z\right)^2 \\ &+ \frac{1}{2}\left(\frac{1}{m^*} + \mathcal{A}(z)\right)\left(\hat{p}_y - \frac{e}{c}B_x z + \frac{e}{c}B_z x\right)^2 . \end{aligned} \tag{5}$$

Here $V(z)$ is the conduction band potential, e is the absolute value of the electron charge and c is the speed of light in vacuum.

For 2D electron gas the in-plane magnetic field may be treated as a small perturbation [11]. To the second order in $B_\|$ this leads to the diamagnetic energy shift and an increase (for ground electric subband) of EM in the direction perpendicular to the direction of the in-plane magnetic field. The native anisotropy of EM may be treated as a small perturbation too. For simplicity we assume that $B_\|$ is parallel either $[1\bar{1}0]$ or $[110]$ so that $B_x B_y = 0$. Including all terms to the second order in $B_\|$ and first in $\mathcal{A}$ we obtain for the zeroth subband

$$\begin{aligned} \hat{H}_0 &= E_0 + \frac{e^2}{2m^*c^2}\left(B_x^2 + B_y^2\right)\left(\left\langle z^2\right\rangle_{00} - \langle z\rangle_{00}^2\right) \\ &+ \frac{1}{2m^*}\left(1 - \frac{\Delta_N}{2} - \frac{B_y^2}{B_\|^2}\Delta_B\right)\left(\hat{p}_x + \frac{e}{c}B_y\langle z\rangle_{00}\right)^2 \\ &+ \frac{1}{2m^*}\left(1 + \frac{\Delta_N}{2} - \frac{B_x^2}{B_\|^2}\Delta_B\right)\left(\hat{p}_y + \frac{e}{c}B_z x - \frac{e}{c}B_x\langle z\rangle_{00}\right)^2 . \end{aligned} \tag{6}$$

The values of the native and magnetic field induced anisotropies of EM are

$$\Delta_N = 2m^*\langle\mathcal{A}(z)\rangle_{00}, \qquad \Delta_B = \frac{2e^2B_\|^2}{m^*c^2}\sum_m{}' \frac{|\langle z\rangle_{0m}|^2}{E_m - E_0}. \tag{7}$$

Here E_m is the mth electric subband edge energy at $B = 0$. Using the rough estimations below let us evaluate Δ_N and Δ_B at $B_\| = 0.5$ T (in experiment [2] such in-plane magnetic field, when $B_\|$ along [110], makes initially anisotropic magnetoresistance essentially isotropic; higher $B_\|$ reorient the direction of low resistance).

$$\langle\mathcal{A}(z)\rangle_{00} \sim \frac{2\langle s \mid \hat{p}_x \mid X\rangle D_{XY}\langle Y \mid \hat{p}_y \mid s\rangle}{m_0^2E_g^2}\langle\delta(z)\rangle_{00} \sim \frac{D_{XY}}{m^*E_g}10^{-2}\text{Å}^{-1}. \tag{8}$$

Here $E_g = 1.5$ eV is the band gap, $m^* = 0.067m_0$, and $D_{XY} \sim 0.2$ eVÅ (in [9] it was found $D_{XY} \sim 0.5$ eVÅ for GaAs/AlAs). For Δ_B we need also

$$\sum_m{}' \frac{|z_{0m}|^2}{E_m - E_0} \sim \frac{(50\,\text{Å})^2}{0.01\,\text{eV}}. \tag{9}$$

Finally we have

$$\Delta_N = 0.27 \cdot 10^{-2} = 0.27\%, \qquad \Delta_B = 0.33 \cdot 10^{-2} = 0.33\%. \tag{10}$$

Matching of these values coming from quite different mechanisms is very good. Now we may conclude that as the in-plane magnetic field $B_{\parallel} \approx 0.5$ T has a strong influence on the direction of the stripes and the value of the ratio R_{xx}/R_{yy}, the native anisotropy of the in-plane EM can be that mechanism making the stripes coherent over the macroscopic size of the studied samples. If so, from the experiment [2] we may conclude that $\langle \mathcal{A}(z) \rangle_{00} < 0$. Moreover, knowing the parameters of the structure more definite (or getting the magnitude of the magnetic field induced EM anisotropy from experiments) one may deduce $\langle \mathcal{A}(z) \rangle_{00}$ from the dependence of the magnetoresistance anisotropy versus in-plane magnetic field [2]. The magnitude of the parameter that governs the native in-plane EM anisotropy may become one of the characteristics of the heterointerface [8].

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References

[1] M. P. Lilly, *et al.*, *Phys. Rev. Lett.* **82** 394 (1999);
R. R. Du, *et al.*, *Solid State Commun.* **109** 389 (1999).

[2] M. P. Lilly, *et al.*, *Phys. Rev. Lett.* **83** 824 (1999).

[3] W. Pan, *et al.*, cond-mat/9903160 at xxx.lanl.gov.

[4] A. A. Koulakov, *et al.*, *Phys. Rev.* B **54** 1853 (1996).

[5] T. Jungwirth, *et al.*, *Phys. Rev.* B **60** 15574 (1999).

[6] H. Kroemer, cond-mat/9901016 at xxx.lanl.gov.

[7] B. Jusserand, *et al.*, *Phys. Rev.* B **51** 4707 (1995).

[8] E. E. Takhtamirov and V. A. Volkov, *Zh. Eksp. Teor. Fiz.* **116** 1843 (1999) [*JETP* **89** 1000 (1999)].

[9] E. L. Ivchenko, *et al.*, *Phys. Rev.* B **54** 5852 (1996).

[10] O. Krebs, *et al.*, *Semicond. Sci. Technol* **12** 938 (1997).

[11] T. Ando, *et al.*, *Rev. Mod. Phys.* **54** 437 (1982).